Chapter 5
Deformation and Settlement

5-1. Scope

This chapter describes the necessary elements for estimating and treating settlement, or heave, of structures that are caused by the deformation of the foundation rock. This chapter is subdivided into four sections. Topic areas for the four sections include categories of deformation, analytical methods for predicting the magnitude of deformation, estimating allowable magnitudes of deformation, and methods available for reducing the magnitude of deformation.

Section I
Categories of Rock Mass Deformation

5-2. General

Deformations that may lead to settlement or heave of structures founded on or in rock may be divided into two general categories: time-dependent deformations and time-independent deformations.

5-3. Time-Dependent Deformations

Time-dependent deformations can be divided into three different groups according to the mechanistic phenomena causing the deformation. The three groups include consolidation, swelling, and creep.

a. Consolidation. Consolidation refers to the expulsion of pore fluids from voids due to an increase in stress. As a rule, consolidation is associated with soils rather than rock masses. However, rock masses may contain fractures, shear zones, and seams filled with clay or other compressible soils. Sedimentary deposits with interbedded argillaceous rock such as shales and mud stones may also be susceptible to consolidation if subjected to sufficiently high stresses. Consolidation theory and analytical methods for predicting the magnitude of consolidation are addressed in EM 1110-1-1904 and in Instruction Report K-84-7 (Templeton 1984).

b. Swelling. Certain expansive minerals, such as montmorillonite and anhydrite, react and swell in contact with water. Upon drying, these minerals are also susceptible to shrinking. The montmorillonite minerals are generally derived from alteration of ferromagnesian minerals, calcic feldspars, and volcanic rocks and are common in soils and sedimentary rocks. Anhydrite represents gypsum without its water of crystallization and is usually found as beds or seams in sedimentary rock as well as in close association with gypsum and halite in the evaporite rocks. Guidance on procedures and techniques for predicting the behavior of foundations on or in swelling minerals is contained in EM 1110-1-1904, TM 5-818-1, and Miscellaneous Paper GL-89-27 (Johnson 1989).

c. Creep. Creep refers to a process in which a rock mass continues to strain with time upon application of stress. Creep can be attributed to two different mechanisms; mass flow and propagation of microfractures. Mass flow behavior is commonly associated with certain evaporite rock types such as halite and potash. Creep associated with microfracture propagation has been observed in most rock types. Figure 5-1 shows a typical strain-time curve for various constant stress levels. As indicated in Figure 5-1, the shapes of the strain-time curve are a function of the magnitude of the applied stress. Creep will generally occur if the applied stress is within the range associated with nonstable fracture propagation. The transition between stable and nonstable fracture propagation varies, depending upon rock type, but typically is on the order of, at least, 50 percent of the uniaxial compressive strength. Most structures founded on rock generate stress levels well below the transition level. Hence, creep is generally not a problem for the majority of Corps projects. Structures founded on weak rock are the possible exceptions to this rule. Although standardized procedures are available to estimate creep properties of intact rock specimens (i.e. RTH-205) what these properties mean in terms of rock mass behavior is poorly understood. For this reason, estimates of creep response for structures founded on rock masses require specialized studies and, in some cases, research.

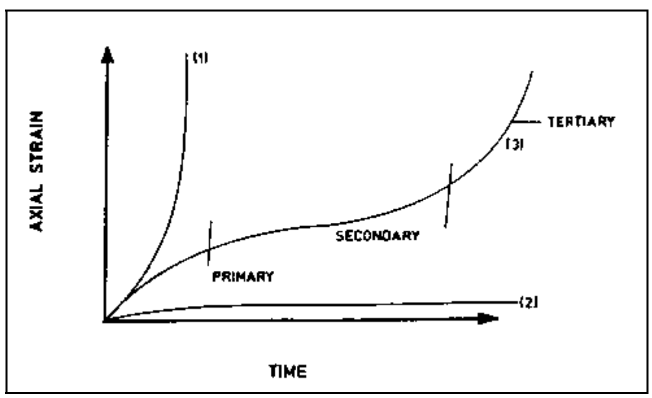

Figure 5-1. Postulated strain-time curves at (1) very high maintained stress levels, (2) moderate maintained stress levels, and (3) high maintained stress levels (from Farmer 1983)

5-4. Time-Independent Deformations

Time-independent deformations refer to those deformations which are mechanistically independent of time. Time-independent deformations include deformations generated by prefailure elastic strains, post-failure plastic strains, and deformations resulting from large shear induced or rotational displacements. Prudent foundation designs preclude consideration of post-failure behavior. Hence, time-independent deformations, as relating to foundation design, refer to deformations that occur as a result of prefailure elastic strains. Analytical methods for estimating rock mass deformations discussed in Section II of this chapter pertain to elastic solutions.

Section II
Analytical Methods

5-5. General

Analytical methods for calculating deformations of foundations may be divided into two general groups, closed form mathematical models and numerical models. The choice of a method in design use depends on how well a particular method models the design problem, the availability, extent, and precision of geological and structural input parameters, the intended use of calculated deformations (i.e. preliminary or final design), and the required accuracy of the calculated values.

5-6. Closed Form Methods

Closed form methods refer to explicit mathematical equations developed from the theory of elasticity. These equations are used to solve for stresses and strains/deformations within the foundation rock as a function of structure geometry, load and rigidity and the elastic properties of the foundation rock. Necessary simplifying assumptions associated with the theory of elasticity impose certain limitations on the applicability of these solutions. The most restrictive of these assumptions is that the rock is assumed to be homogeneous, isotropic and linearly elastic. Poulos and Davis (1974) provide a comprehensive listing of equations, tables, and charts to solve for stresses and displacements in soils and rock. Complex loadings and foundation shapes are handled by superposition in which complex loads or shapes are reduced to a series of simple loads and shapes. Conditions of anisotropy, stratification, and inhomogeneity are treated with conditional assumptions. If sound engineering judgment is exercised to insure that restrictive and conditional assumptions do not violate reasonable approximations of prototype conditions, closed form solutions offer reasonable predictions of performance.

a. Input parameters. Closed form solutions require, as input parameters, the modulus of elasticity and Poisson's ratio. For estimates of deformation/settlement in rock, the modulus of deformation, E_d, is used in place of modulus of elasticity. Techniques for estimating the modulus of deformation are described in Chapter 4 of this manual. Poisson's ratio typically varies over a small range from 0.1 to 0.35. Generally, the ratio values decrease with decreasing rock mass quality. Because of the small range of likely values and because solutions for deformation are relatively insensitive to assigned values, Poisson's ratio is usually assumed.

b. Depth of influence. Stresses within the foundation rock that are a result of foundation loads decrease with depth. In cases where the foundation is underlain by multi-layered rock masses, with each layer having different elastic properties, the depth of influence of the structural load must be considered. For the purpose of computing deformation/settlement, the depth of influence is defined as the depth at which the imposed stress acting normal to the foundation plane diminishes to 20 percent of the maximum stress applied by the foundation. If there is no distinct change in the elastic properties of the subsurface strata within this depth, elastic solutions for layered media need not be considered. Poulus and Davis (1974) and Naval Facilities Engineering Command, NAVFAC DM-7.1 (1982) provide equations and charts based on Boussinesq's equations for estimating stresses with depth imposed by various foundation shapes and loading conditions.

c. Layered foundation strata. Poulus and Davis (1974) provided procedures for estimating the deformation/settlement of foundations with the depth of influence for up to four different geologic layers. Multilayer strata, in which the ratios of moduli of deformation of any of the layers does not exceed a factor of three, may be treated as a single layer with a representative modulus of deformation equivalent to the weighted average of all layers within the depth of influence. A weighted average considers that layers closer to the foundation influence the total deformation to a greater extent than deeper layers. Figure 5-2 shows a foundation underlain by a multi-layer strata containing n number of layers within the depth of influence. The weighted average modulus of deformation may be obtained from Equation 5-1.

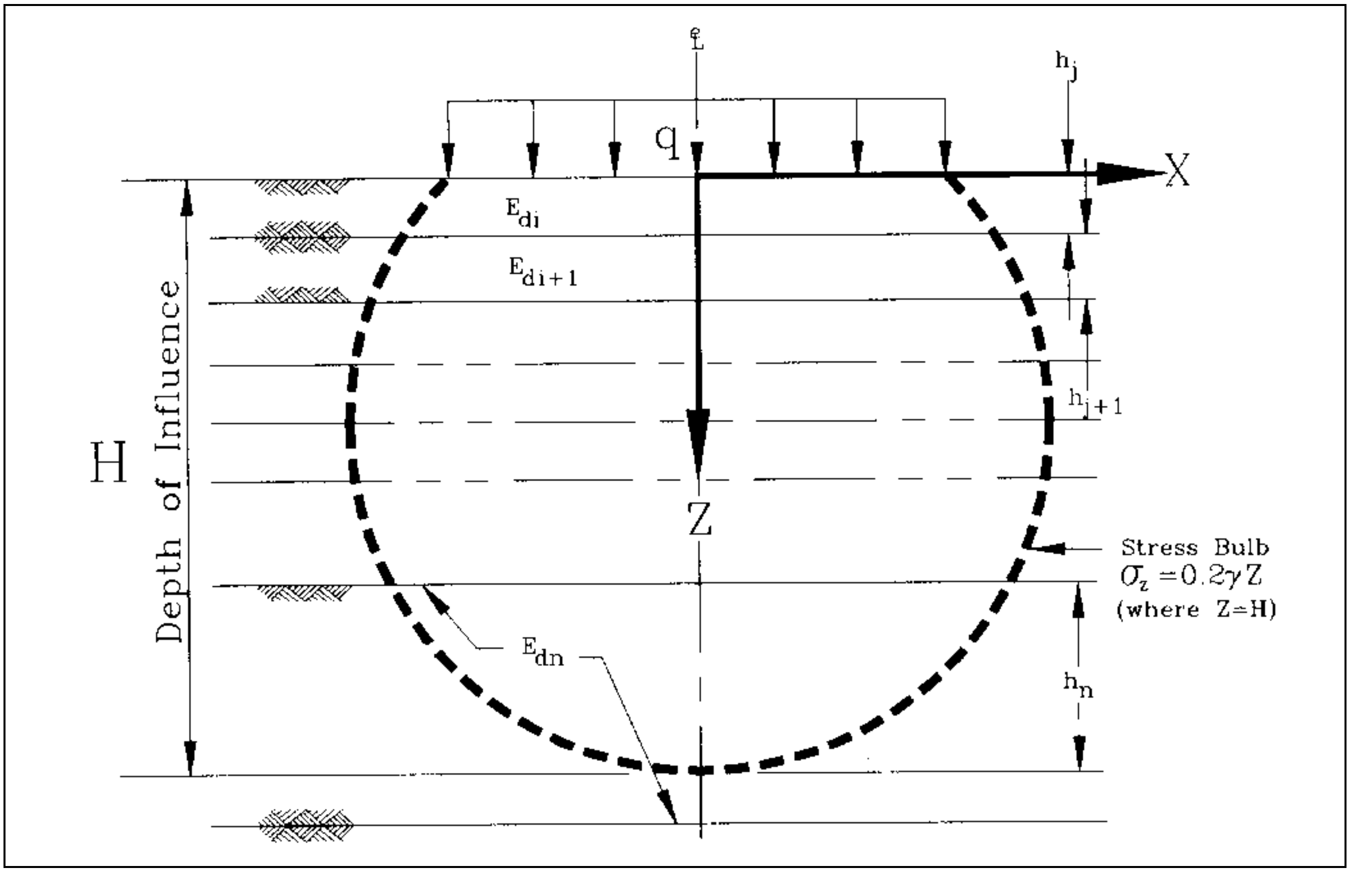

Figure 5-2. Hypothetical foundation underlain by a multilayer strata containing *n* number of layers within the depth of influence

$$E_{dw} = \frac{\sum_{i=1}^{n} \left(E_i \Big/ \sum_{j=1}^{i} h_j \right)}{\sum_{i=1}^{n} \left(1 \Big/ \sum_{j=1}^{i} h_j \right)} \tag{5-1}$$

where

E_{dw} = weighted average modulus of deformation

E_{di}, E_{di+1}--E_{dn} = modulus of deformation of each layer. The ratios of any E_{di}, E_{di+1}---E_{dn} terms <3

h_j, h_{j+1}---h_n = thickness of each layer

n = Number of layers

d. Solutions for uniformly loaded rectangular foundations. Rectangular foundations are common shapes for footings and other structures. Solutions for deformation of uniformly loaded foundations are divided into two categories, flexible foundations and rigid foundations.

(1) Flexible foundations. Flexible foundations lack sufficient rigidity to resist flexure under load. As indicated in Figure 5-3 the maximum deformation of a uniformly loaded flexible rectangular foundation occurs at the center of the foundation. The maximum deformation (point *a* in Figure 5-3) can be estimated from the solution of Equation 5-2.

$$\delta_a = \frac{1.12\ qB\ (1 - \mu^2)\ (L/B)^{1/2}}{E_d} \tag{5-2}$$

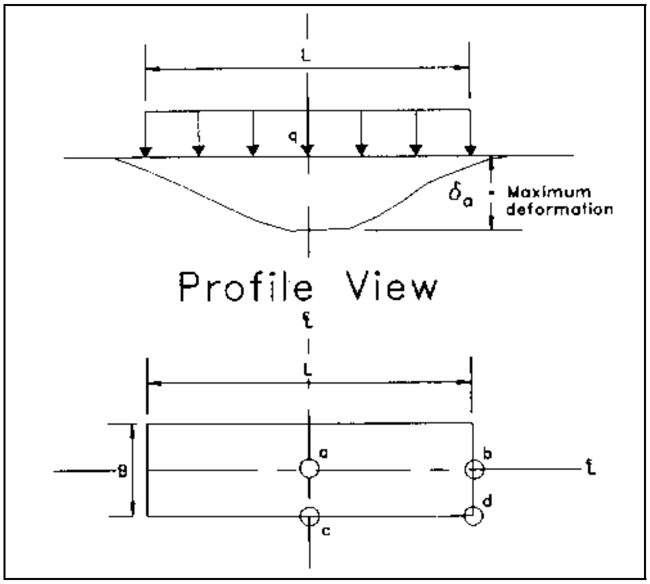

Figure 5-3. Typical deformation profile under a uniformly loaded, rectangular shaped, flexible foundation

where

δ_a = maximum deformation (deformation at point *a* in Figure 5-3)

q = unit load (force/area)

B = foundation width

L = foundation length

μ = Poisson's ratio of the foundation rock

E_d = modulus of deformation of the foundation rock

Estimates of the deformation of points *b*, *c*, and *d* in Figure 5-3 can be obtained by multiplying the estimated deformation at point *a* (Equation 5-2) by a reduction factor obtained from Figure 5-4.

(2) Rigid foundations. Rigid foundations are assumed to be sufficiently rigid to resist flexure under load. Examples include concrete gravity structures such as intake and outlet structures. Rigid uniformly loaded foundations settle uniformly. The estimated deformation can be obtained by multiplying the maximum estimated deformation for a flexible foundation of the same dimensions from Equation 5-2 by the reduction factor obtained from the average for rigid load curve in Figure 5-4.

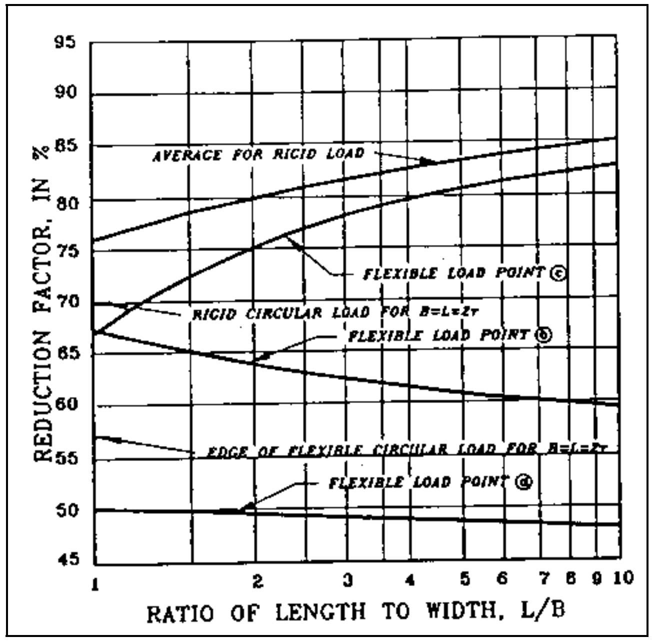

Figure 5-4. Reduction factor in percent of settlement under the center of a flexible rectangular shaped foundation (from NAVDOCKS DM-7)

e. Linearly varying loads. In practice, most gravity retaining structures, such as monoliths of gravity dams and lock walls, do not uniformly distribute loads to the foundation rock. As indicated in Figure 5-5, loading of

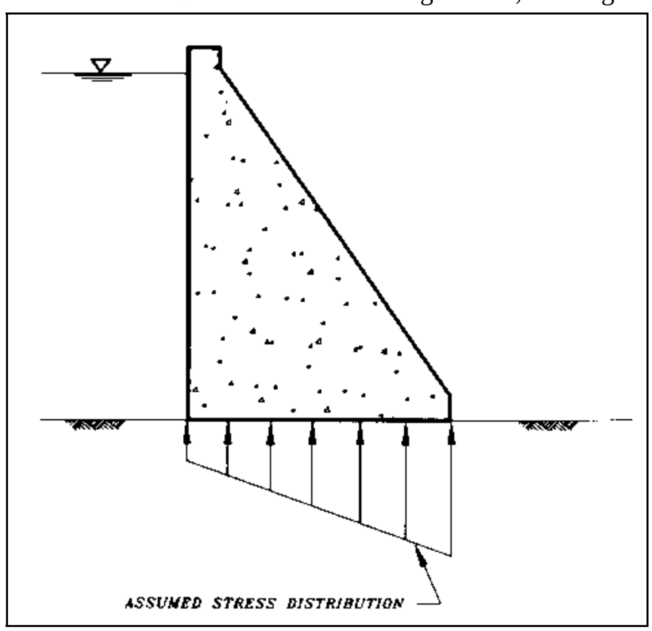

Figure 5-5. Assumed linearly varying stress distribution

these structures may be approximated by assuming linearly varying load distributions. A complete deformation/settlement analyses require the calculation of deformations in both the horizontal and vertical planes. Closed form solutions are available to address linearly varying loads (Poulos and Davis 1974). However, a complete solution requires that the loading conditions be divided into a number of segments. The calculated deformations of each segment are summed to provide a complete solution. In this respect, closed form solutions are tedious, and, because of simplifying assumptions, provide only approximate solutions.

5-7. Numerical Models

Numerical models refer to those analytical methods which, because of their complexity, require the solution of a large number of simultaneous equations. Such solutions are only reasonably possible with the aid of a computer. In many cases numerical models provide the only practical alternative for estimating deformation/settlement of structures subjected to complicated loading conditions and/or are founded on anisotropic, nonhomogeneous rock. Numerical approaches can be separated into two general groups: discontinuum and continuum.

a. Discontinuum models. Discontinuum models feature numerical approaches involving equations of motion for rigid particles or blocks. Such models are frequently referred to as discrete element models. Discontinuum approaches are primarily used when analyzing the stability and/or kinematics of one or more independent and recognizable rock blocks. Because the rock blocks are treated as rigid bodies, discontinuum models are not used to analyze magnitudes of rock deformations.

b. Continuum models. Continuum approaches include the finite element, finite difference, and boundary element methods. All these methods may be used to solve for estimated magnitudes of deformation/settlement. However, the finite element method is the most popular. Numerical modeling of foundation responses dictates the use of constitutive relationships which define material stress-strain behavior. Finite element codes are available which incorporate sophisticated constitutive relationships capable of modeling a variety of nonlinear and/or time-dependent stress-strain behavior. Analytical capabilities offered by some of the more sophisticated codes exceed the ability of the geotechnical engineer to provide meaningful material property parameters. For foundation stress levels and underlying rock types encountered for the majority of structures, reasonable estimates of deformation/settlement can be obtained from linear elastic codes with the modulus of deformation as the primary input parameter. Table 5-1, although not all inclusive, summarizes some of the finite element codes that are commercially available. The choice of code to use should reflect the ability of the code to model the problem at hand and the preference of District office geotechnical professionals charged with the responsibility of settlement analyses.

Section III
Allowable Settlement

5-8. General

For structures founded on rock, the total deformation/settlement seldom controls design. The design for, or control of, differential settlement between critical elements of a structure is essential for the proper and safe functioning of that structure. The total settlement should be computed at a sufficient number of points to establish the overall settlement pattern. From this pattern, the differential settlements can be determined and compared with recommended allowable values.

5-9. Mass Concrete Structure

Mass concrete structures are uniquely designed and constructed to meet the needs of a particular project. These structures vary in size, shape, and intended function between projects. As a result, the magnitude of differential settlement that can be tolerated must be established for each structure. Specifications for the allowable magnitudes of differential deformation/settlement that can be tolerated require the collective efforts of structural and geotechnical professionals, working together as a team. The magnitude of allowable differential movement should be sufficiently low so as to prevent the development of shear and/or tensile stresses within the structure in excess of tolerable limits and to insure the proper functioning of movable features such as lock and flood control gates. For mass concrete structures founded on soft rock, where the modulus of deformation of the rock is significantly less than the elastic modulus of the concrete, there is a tendency for the foundation rock to expand laterally thus producing additional tensile stresses along the base of the foundation. Deere et al. (1967) suggested the following criteria for evaluating the significance of the ratios between the modulus of deformation of the rock (E_{dr}) and the elastic modulus of the concrete (E_c):

Table 5-1
Summary of Finite Element Programs

Program	Capabilities: 2D and 3D Solid Elements	Boundary Elements	Crack Elements	Linear Elastic Anisotropic	Nonlinear Elastic	Plasticity	Viscoelastic or Creep	Interactive Graphics
ABAQUS	X			X	X	X	X	X
ANSYS	X		X	X	X	X	X	X
APPLE-SAP	X	X		X				
ASKA	X		X	X	X	X	X	X
BEASY	X	X				X		
BERSAFE		X	X	X	X	X	X	X
BMINES	X		X	X	X	X	X	X
DIAL	X	X	X	X	X	X	X	X
MCAUTO STRUDL	X			X				X
MSC/ NASTRAN	X		X	X	X	X	X	X
PAFEC	X	X	X	X	X	X	X	X
SAP(WES)	X			X				X
E^3SAP	X			X				X
NONSAP	X		X	X	X	X		X
TITUS	X	X	X	X	X	X		X

a. If E_{dr}/E_c >0.25, then the foundation rock modulus has little effect on stresses generated within the concrete mass.

b. If 0.06 <E_{dr}/E_c <0.25, the foundation rock modulus becomes more significant with respect to stresses generated in the concrete structure. The significance increases with decreasing modulus ratio values.

c. If E_{dr}/E_c <0.06, then the foundation rock modulus almost completely dominates the stresses generated within the concrete. Allowable magnitudes of deformation, in terms of settlement heave, lateral movement, or angular distortion for hydraulic structures should be established by the design team and follow CECW-ED guidance.

Section IV
Treatment Methods

5-10. General

In design cases where the magnitudes of differential deformation/settlement exceed allowable values the team of structural and geotechnical professionals charged with the responsibility of foundation design must make provisions for either reducing the magnitude of differential movement or design the structure to accommodate the differential deformation. A discussion of the latter option is beyond the scope of this manual. There are two approaches available for reducing the magnitude of differential deformation/settlement: improve the rock mass deformation characteristics and/or modification of the foundation design.

5-11. Rock Mass Improvement

Rock mass improvement techniques refer to techniques which enhances the ability of a rock mass to resist deformation when subjected to an increase in stress. The two techniques that are available include rock reinforcement and consolidation grouting. As a rule, techniques for increasing the modulus of deformation of a rock mass are limited to special cases where only relatively small reductions in deformation are necessary to meet allowable deformation/settlement requirements.

a. Rock reinforcement. Rock reinforcement (i.e. rock bolts, rock anchor, rock tendon, etc.) is primarily used to enhance the stability of structures founded on rock. However, in specialized cases, constraint offered by a systematic pattern of rock reinforcement can be effective in reducing structural movement or translations (for example, rotational deformations of retaining structures). Guidance for rock reinforcement systems is provided in Chapter 9.

b. Consolidation grouting. Consolidation grouting refers to the injection of cementitious grouts into a rock mass for the primary purpose of increasing the modulus of deformation and/or shear strength. The enhancement capabilities of consolidation grouting depend upon rock mass conditions. Consolidation grouting to increase the modulus of deformation is more beneficial in highly fractured rock masses with a predominant number of open joints. Before initiating a consolidation grouting program a pilot field study should be performed to evaluate the potential enhancement. The pilot field study should consist of trial grouting a volume of rock mass representative of the rock mass to be enhanced. In-situ deformation tests (discussed in Chapter 4) should be performed before and after grouting in order to evaluate the degree of enhancement achieved. Guidance pertaining to consolidation grouting is provided in EM 1110-2-3506 and Technical Report REMR-GT-8 (Dickinson 1988).

5-12. Foundation Design Modifications

The most effective means of reducing differential deformation/settlement are through modification of the foundation design. A variety of viable modifications is possible, but all incorporate one or more of three basic concepts: reduce stresses applied to the foundation rock; redistribute the applied stresses to stiffer and more competent rock strata; and in cases involving flexible foundations, reduce maximum deformations by increasing the foundation stiffness. The choice of concept incorporated into the final design depends on the foundation rock conditions, structural considerations, associated cost, and should be accomplished by the design team in accordance with CECW-ED guidance.